

Northumbria Research Link

Citation: Tiong, Michelle, Gholami, Raoof and Rahman, Muhammad (2019) Cement degradation in CO2 storage sites: a review on potential applications of nanomaterials. Journal of Petroleum Exploration and Production Technology, 9 (1). pp. 329-340. ISSN 2190-0558

Published by: Springer

URL: <https://doi.org/10.1007/s13202-018-0490-z> <<https://doi.org/10.1007/s13202-018-0490-z>>

This version was downloaded from Northumbria Research Link:
<http://nrl.northumbria.ac.uk/id/eprint/45487/>

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: <http://nrl.northumbria.ac.uk/policies.html>

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)



Cement degradation in CO₂ storage sites: a review on potential applications of nanomaterials

Michelle Tiong¹ · Raoof Gholami¹ · Muhammad Ekhlasur Rahman²

Received: 18 September 2017 / Accepted: 10 May 2018 / Published online: 31 May 2018
© The Author(s) 2018

Abstract

Carbon capture and sequestration (CCS) has been employed to reduce global warming, which is one of the critical environmental issues gained the attention of scientific and industrial communities worldwide. Once implemented successfully, CCS can store at least 5 billion tons of CO₂ per year as an effective and technologically safe method. However, there have been a few issues raised in recent years, indicating the potential leakages paths created during and after injection. One of the major issues might be the chemical interaction of supercritical CO₂ with the cement, which may lead to the partial or total loss of the cement sheath. There have been many approaches presented to improve the physical and mechanical properties of the cement against CO₂ attack such as changing the water-to-cement ratio, employing pozzolanic materials, and considering non-Portland cements. However, a limited success has been reported to the application of these approaches once implemented in a real-field condition. To date, only a few studies reported the application of nanoparticles as sophisticated additives which can reinforce oil well cements. This paper provides a review on the possible application of nanomaterials in the cement industry where physical and mechanical characteristics of the cement can be modified to have a better resistance against corrosive environments such as CO₂ storage sites. The results obtained indicated that adding 0.5 wt% of Carbon NanoTubes (CNTs) and NanoGlass Flakes (NGFs) can reinforce the thermal stability and coating characteristics of the cement which are required to increase the chance of survival in a CO₂ sequestered site. Nanosilica can also be a good choice and added to the cement by as much as 3.0 wt% to improve pozzolanic reactivity and thermal stability as per the reports of recent studies.

Keywords CO₂ storage sites · Cement design · Carbonation · Nano materials · Degradation

Introduction

Carbon dioxide (CO₂) sequestration is the technology developed in the past decades to reduce the amount of greenhouse gases increasingly released into the atmosphere. In this technique, which is also known as Carbon Capture and Storage (CCS), CO₂ as a dominant greenhouse gas is captured in industrial sites and injected into deep geological formations for thousands of years (Gaurina-Medimurec et al. 2010). The CCS technology has been initiated 20 years ago when a million metric tons per year of CO₂ was injected into an aquifer beneath the North Sea (Benson and Cole 2008). Canada and

Algeria followed the footsteps and sequestered over 20 million tons (Mt) of CO₂ in their deep geological sites ever since (Benson and Cole 2008; Takase et al. 2010). According to the International Energy Agency (IEA), the CCS can help to reduce more than 13% of cumulative greenhouse gas emission by 2050 and restrict the global increase of temperature. By 2015, there were 15 large-scale facilities around the world capturing 27 million tones (Mt) of CO₂ every year (International Energy Agency 2015). This would be a significant contribution into the reduction of global greenhouse gas emissions needed to restraint climate change.

Coal beds, saline aquifers, and depleted oil reservoirs are often chosen for CO₂ storage purposes, among which depleted reservoirs are the best options due to their geological history, integrity and infrastructures. Abundant and closed wells of these reservoirs are the best conduits to inject CO₂, where the injection interval is cemented to avoid leakages. However, chemical degradations and mechanical failures induced due to the reaction with supercritical (Sc)

✉ Raoof Gholami
raoof.gholami@curtin.edu.my

¹ Department of Petroleum Engineering, Curtin University, Sarawak, Malaysia

² Department of Civil Engineering, Curtin University, Sarawak, Malaysia

CO₂ and carbonic acid under reservoir conditions may create leakage paths in the cement, causing seepage of CO₂ to the surface and other valuable subsurface resources (Xu et al. 2007; Bachu and Bennion 2009; Zhang et al. 2013; Ansarizadeh et al. 2015). In fact, the class G cement, which is commonly used in the primary or secondary cementing stages, is very vulnerable and may lose its durability once exposed to supercritical (sc) CO₂. As a result, its mechanical and physical properties such as compressive strength, permeability, and porosity might change unfavorably, resulting in leakage of CO₂ from the storage sites (Zhang et al. 2013; Ansarizadeh et al. 2015).

There have been several methods proposed in recent years to improve the mechanical and transfer characteristics of the cement used for sequestration practices. Changing the water-to-cement ratio, applying pozzolanic materials and employing non-Portland cement are the most important approaches proposed so far with limited success once tested under reservoirs conditions (Abid et al. 2015). Employing nanoparticles might be another approach that worth consideration as a solution for reinforcing the cement. This is mainly because chemical and mechanical properties of materials are changed when their particle size is reduced. It is also known that Calcium–Silicate–Hydrate (C–S–H), which is one of the main components required to resist against the CO₂ attack, is widely available in a high order structure at the nanoscale (Abid et al. 2015; Arina and Irawan 2010). The benefits of using nanoparticles, such as nanosilica (SiO₂), nanoalumina (Al₂O₃), clay nanocomposites, nanotitanium oxide (TiO₂), carbon nanotubes (CNTs), and nanoglass flake (NGFs) have been widely presented in the building and polymer industries (Abid et al. 2015; Jahangir and Kazemi 2014; Lee 2012; Ghadami et al. 2014). However, there have been a very limited discussion on their potential applications in the oil and gas industries, especially for CO₂ sequestration sites. The aim of this paper is to provide a review of the characteristics of different nanoparticles and evaluate their potential applications in the cement used for the storage sites. This may shed some lights as to how the physical and mechanical characteristics of the cement can be improved for a safer storage of CO₂.

Background

In this section, attempts are made to provide a better insight into the interactions taking place in storage sites between the cement and CO₂. The importance of CO₂ sequestration as well as physical and chemical phenomena involved are discussed and approaches developed so far to resist the CO₂ attack are presented.

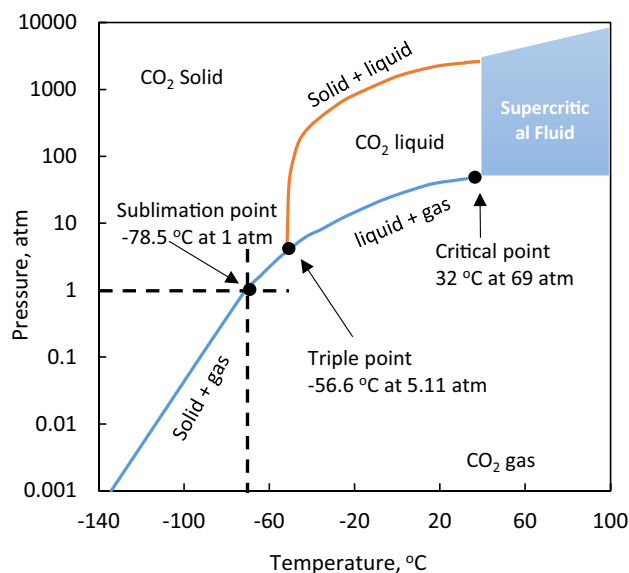


Fig. 1 CO₂ phase diagram [modified after (Oldenburg 2007; Waseem Arshad et al. 2017)]

CO₂ sequestration in deep geological formations

CO₂ storage sites are often referred to as deep geological formations with a storage capacity of 675–900 billion tons (Ansarizadeh et al. 2015; Benson and Cole 2008). It is a common practice for the oil and gas industry to inject CO₂ into particular deep (more than 800 m) geological formations (reservoirs) to increase the petroleum production, which is also known as Enhanced Oil Recovery (EOR). When these reservoirs are completely depleted and verified as a safe geological storage sites, CO₂ sequestration is considered as part of the CCS technology in the field (Gaurina-Medimurec et al. 2010).

Once injected into the storage sites, CO₂ must be monitored carefully as it appears in different phases under diverse temperature and pressure conditions (see Fig. 1). For instance, at the ambient temperature, CO₂ appears as a gas, but it becomes a supercritical fluid under the temperature of 32 °C and the pressure of 7 MPa (IPCC 2005; Oldenburg 2007), which often happens at the depth of greater than 800 m.

Cement systems for CO₂ sequestration

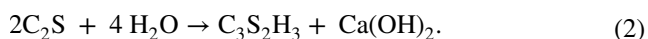
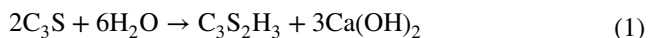
Secondary cementing is done to seal off the wells used to inject CO₂ in the reservoir. A good well cement should have an appropriate thickening time, a good rheology, a low water

Table 1 Major components of Portland cement (modified from Adams and Charrier 1985)

Compound	Chemical composition	Cement chemist notation	Concentration (wt %)	Purpose
Tricalcium silicate	$(\text{CaO})_3 \cdot \text{SiO}_2$	C_3S	55–65	Enhances the strength and develops early strength
Dicalcium silicate	$(\text{CaO})_2 \cdot \text{SiO}_2$	C_2S	15–25	Hydrates slowly, strength generated over extended period of time
Tricalcium aluminate	$(\text{CaO})_3 \cdot \text{Al}_2\text{O}_3$	C_3A	8–14	Promotes rapid hydration, affects thickening time and initial setting of the cement, and makes the cement vulnerable to sulfate attack
Tetracalcium aluminoferrite	$(\text{CaO})_4 \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	C_3AF	8–12	Responsible for slow hydration

loss efficiency, and no free water bleeding (Lesti et al. 2013). There are eight classes of cements listed in the American Petroleum Institute (API)¹ standard, categorized based on their specifications and functionality. Among all classes, Class G (Portland Cement) is the most common one. In fact, Portland cement is commonly used on many occasions due to its accessibility and adaptability to different subsurface conditions. This type of cement consists of four main components, including Tricalcium Silicate (C_3S), Dicalcium Silicate (C_2S), Tricalcium Aluminate (C_3A), and Tetracalcium Aluminoferrite (C_3AF), which give certain functionality to the cement such as enhancing the strength or changing the hydration rate. Table 1 gives a summary of the functionality provided by the cement components.

Tricalcium silicate (C_3S) is the most abundant component of the cement, hydrating faster than others (Nelson 1990). When water is mixed with the cement, hydration takes place and the compressive strength develops, which expressed as (MacLaren and White 2003; Omosebi et al. 2016):

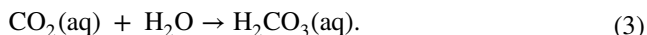


Hydration of aluminate, tetracalcium aluminoferrite (C_3AF), is similar to tricalcium aluminate (C_3A), which forms ettringite when it reacts with gypsum. As a result, the production of calcium–silicate–hydrate (C–S–H) is more than $\text{Ca}(\text{OH})_2$ due to the abundance of C_3S . This calcium–silicate–hydrate is a very important component acting as the binder of the cement.

Portland cement degradation: carbonation and bicarbonation

To understand the chemical reactions taking place between supercritical carbon dioxide (scCO_2) and Portland cement, Kutchko et al. (2007) carried out an experimental study to simulate a real reservoir condition (i.e., the temperature of 50 °C and the pressure of 30.3 MPa with a pH of 12.3). They indicated that the cement degradation is linked to the structural transformation of C–S–H, carbonation of portlandite ($\text{Ca}(\text{OH})_2$) and the leaching of calcium carbonate (CaCO_3).

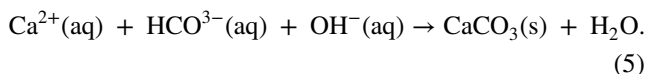
In fact, when CO_2 is injected into a storage site, it dissolves into the brine, which is often left in the reservoir after production, and forms carbonic acid (H_2CO_3) as expressed in Eq. (3). This leads to a significant reduction of pH:



As carbonic acid diffuses into the hydrated cement, Portlandite is attacked, as expressed in Eq. (4), at a very fast rate due to its higher reactivity (Omosebi et al. 2016). This interaction brings an equilibrium to the solution:



However, due to the consummation of Portlandite and leaching of Ca^{2+} out of the cement matrix, the porosity of the cement increases and calcium carbonate (CaCO_3) is precipitated, as addressed by Eq. (5). Under these circumstances, CaCO_3 acts like a filler and occupies the pore space of the cement, causing a significant reduction in porosity. In fact, formation of CaCO_3 not only decreases the porosity and permeability by densification of the cementitious matrix, but also increases the compressive strength. This process, which is known as carbonation, is thermodynamically favored and cannot be avoided (Santra and Sweatman 2011):



Although carbonation improves the cement resistance to CO_2 attack, the crystallization of CaCO_3 would lead to cracking and volume expansion (Abid et al. 2015). This

¹ API standard is a practice that is an accepted worldwide standard which is followed by most of the oil and natural gas companies.

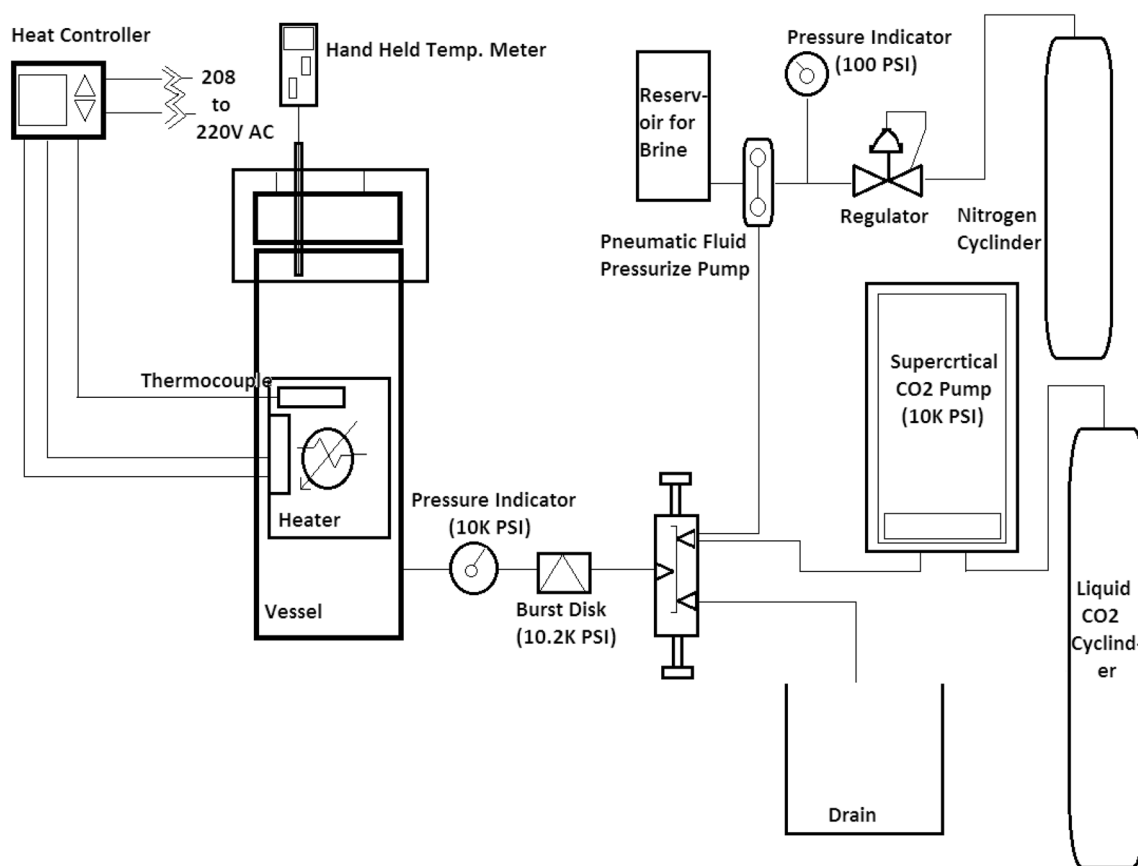
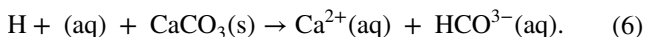


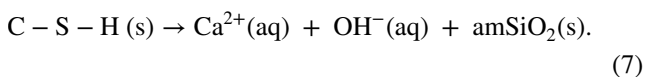
Fig. 2 Schematic view of the static reactor designed and installed at Curtin University Malaysia

would provide a route for CO_2 to migrate easily from the storage site.

When portlandite is completely consumed, CaCO_3 starts to dissolve due to its continuous reaction with fresh carbonic water, which leads to further leaching of Ca^{2+} and domination of HCO_3^- , as expressed by Eq. (6). This dissolution of CaCO_3 is called bicarbonation:



Without CaCO_3 , the remaining C–S–H, which acts as the binding component in the hydrated cement, is converted into amorphous silica gel (amSiO_2), as expressed by Eq. (7). As a result, the amount of Ca^{2+} gradually increases and more pores are created within the cement matrix, which leads to the loss of zonal isolation and migration of CO_2 to the surface and subsurface resources (Kutchko et al. 2007; Zhang and Talman 2014):



Neat cement degradation

Experimental conditions

Many of the laboratory experiments carried out to evaluate cement integrity in a CO_2 rich environment were done using an HPHT vessel. Half of this pressure vessel is often filled with brine (salt water) to have brine saturated CO_2 (carbonic acid), while the upper half contains only scCO_2 which is known as wet CO_2 (Barlet-Gouedard et al. 2009). This configuration allows to simulate a storage site and initiate carbonation of the cement in the presence of CO_2 . Figure 2 shows a schematic view of the pressure vessel installed at Curtin University, Malaysia.

The period of the experiment may vary from a month to a year during which the samples are constantly monitored to evaluate the carbonation rate. To achieve the best result, the carbonation tests under these circumstances are carried out under the static condition where the amount of brine/fresh water initially added to the vessel is maintained (Kutchko et al. 2008). It should be noted that employing fresh water rather than brine would accelerate the degradation of the

Table 2 Developed approaches to improve cement resistance in CO₂ sequestration sites (modified after Abid et al. 2015)

Approaches	Result
Using Pozzolanic material, e.g. fly ash, silica fume, bentonite	Reducing the permeability and quantity of the portlandite. As permeability decreases, the ingress of CO ₃ ²⁻ and carbonation slows down (Kutchko et al. 2008, Duguid and Scherer 2010) Reducing the water content in the cement and decreasing the Ca/Si ratio, causing the creation of a longer chain of C–S–H, which increases the strength of the cement An excessive amount of pozzolanic materials may result in a poor strength development (Kutchko et al. 2008, Laudet et al. 2011)
Decreasing water/cement ratio	Increasing the unhydrated cement clinker which eventually decreases the permeability Increasing the density which may increase the fracture possibilities May result in creating fractures in heavy weight cement (Brandl et al. 2010)
Using non-portland cements	It is not sufficient for a long-term wellbore integrity and not generally recommended because of its accessibility (Bai et al. 2015) The hydration products are resistant to CO ₂ (Takase et al. 2010)
Using special additives	Latex, for example, improves the bonding strength and controls the filtration loss. It allows a good strength development (Duguid and Scherer 2010). The resistance against CO ₂ attack will, however, not be significantly improved due to a low quantity of CaCO ₃ present Epoxy resins will chemically coat the cement but it was degraded when tested at 90 °C and 28 MPa for 31 days (Brandl et al. 2010)
Using nanomaterials	Nanosilica, for example, improves the microstructure and the strength of the cement by decreasing the porosity and permeability of mortar (Zhang et al. 2014) Polymer/clay nanocomposites increase the tensile strength (Barlet-Gouédard et al. 2007) Nanoiron enhances the compressive strength (Barlet-Gouédard et al. 2012)

cement due to the faster rate of CO₂ getting dissolved in fresh water.

Experimental studies

Experimental studies carried out to evaluate cement degradation are often conducted by an HPHT chamber (vessel) to simulate reservoir conditions. These studies are categorized into two classes: (1) cements are exposed to scCO₂ saturated brine and (2) cement samples are solely tested against scCO₂, which is also known as wet scCO₂ (Kutchko et al. 2007, 2008; Barlet-Gouédard et al. 2009; Arina and Irawan 2010; Duguid and Scherer 2010; Laudet et al. 2011). Having done such tests, Barlet-Gouédard et al. (Barlet-Gouédard et al. 2009) suggested that brine should be used for the carbonation test rather than fresh water. They used a 0.4M NaCl brine solution and observed a dramatic fall in the propagation rate of the cement samples after 2 days of exposure to CO₂-saturated brine. To investigate the effect of temperature and pressure on the cement degradation, Arina and Irawan (2010) conducted an experiment by preparing the neat Class G cement according to the API recommended practice. They cured the cement slurry for 8 h at different temperatures (40 and 120 °C) and pressures (10.5 and 14.0 MPa) where it was found that the HPHT condition reduces the compressive strength, causing densification of C–S–H, which would increase the rate of CO₂ penetration. Barlet-Gouédard et al. (2009) found out that the degradation of the cement is faster under high-temperature (90 °C) and high-pressure (20.68 MPa) conditions. They indicated that

the cement morphology is modified by temperature under these circumstances. Laudet et al. (2011) carried out a carbonation test using neat Class G cements exposed to scCO₂ for about 90 days, at the pressure of 8 MPa and two different temperatures of 90 and 140 °C. A faster carbonation front was found at 140 °C due to the mineralogical nature of the hydrates which reduces the cement's transport properties and ultimately limits the carbonation process. They emphasized that the wellbore temperature and pressure should be monitored before the cement design.

To further understand the behavior of Portland cement under sequestered environments, Kutchko et al. (2007, 2008) carried out a series of experiments in which neat class H cement samples were exposed to scCO₂ under the reservoir condition (i.e., the pressure of 30.3 MPa and the temperature of 50 °C). They observed that the cement resistance depends mainly on the curing environment. In fact, the cement cured under HPHT conditions for 28 days had the least amount of CO₂ penetration due to the formation of calcite. This study was further investigated by Kutchko et al. (2008) in which the period of carbonation test was extended from 9 days to 1 year. The results obtained indicated that the carbonation reaction is a diffusion controlled phenomenon for samples exposed to the scCO₂ environment. Duguid and Scherer (2010) did a series of experiments to study the relationship between the cement degradation and pH variation. There was no degradation in the samples exposed to scCO₂ having a leaching solution of pH 5. Hence, they concluded that if CaCO₃ can be dissolved into the formation water, the degradation would stop. This could be the reason

why sandstone reservoirs have a greater carbonation front compared to carbonates. However, this experiment was conducted under dynamic conditions and it may not be a true representative of reservoir conditions.

Knowing that cement degradation taking place under CO₂-rich environments, a number of attempts were made in the past decade to resolve this issue by providing different approaches, which are discussed in the next section.

Developed approaches to improve cement resistance

As per the discussion provided, the carbonation of Portland cement is unavoidable and, hence, a few methodologies were proposed to enhance the cement resistance as reported in Table 2. Looking at Table 2, it seems that nanomaterials have gained the attention of many researchers in the past few years considering their remarkable functionality and proven applications in the construction and building-related applications. It is undeniable that other supplementary materials can improve the overall performance of the cement if properly selected/used. However, the improvement achieved by nanomaterials used so far is significantly higher than the other materials, mainly because of their large surface areas, fast interactions, and favorable pozzolanic components. In the next section, different nanomaterials which were already used or may have applications to improve the efficiency of cements and concretes are presented together with their advantageous and shortcomings. This may provide a deeper insight into the potential applications of these nanomaterials in the oil well cementing.

Nanomaterials

Modification of cement-based materials using nanoparticles is currently recognized as an active research area for the construction and civil industry. In this technique, nanosize ($< 10^{-9}$) additives are included in the mixing procedure to improve the desired properties of the cement and concrete (Lee 2012). This is mainly because nanoatoms can much easily attached to the surface of each particle and increase the surface area-to-volume ratio, which potentially increases the mechanical strength and reduces the porosity of concretes. Moreover, adding nanoparticles promotes the hydration process at the early stages due to the large surface area of particles (Zhang and Li 2011; Choolaei et al. 2012; Meng et al. 2012). Besides, cement is composed mainly of nano/microsize crystals and amorphous calcium-silicate-hydrate (C–S–H). As mentioned earlier, C–S–H acts as the binder

of the cement, which is one of the key components governing the cement's durability. Hence, the nanosized C–S–H particles with an average size of 5–10 nm can significantly reduce the porosity and permeability of the cement (Sobolev 2015). Sanchez and Sobolev (2010) highlighted the following advantageous of adding nanoparticles to the cement:

- Well-dispersed nanoparticles can help to suspend the cement grains and aggregate by increasing the viscosity of the liquid phase. At the same time, they can improve the segregation resistance and workability of the system;
- Nanoparticles fill the voids between the cement grains, ceasing the movement of “free” water;
- Well-dispersed nanoparticles can accelerate the hydration by acting as the centers of the crystallization of cement hydrates;
- Nanoparticles favor the formation of small-sized crystals and small-sized uniform clusters of C–S–H;
- Nanoparticles enhance the structure of the aggregates' contact zone, resulting in a better bond between aggregates and the cement paste;
- Nanoparticles can provide crack arrest and interlocking effects between the slip planes, which improves the toughness, shear, tensile, and flexural strength of the cement-based materials;
- The tremendous surface area/volume ratio of nanomaterials alters the chemical reactions of hydrating cements and enhances their mechanical strength.

However, it should be noted that the nature of nanoparticles, their composition, and dosage may cause some unfavorable changes in the matrix of the cement. As such, cautions must be taken to ensure that the nanoparticles chosen for oil well cementing does not pose any negative impact on the physical and mechanical characteristics of the cement once used. In the next section, some of the most common nanoparticles used in the cement and concrete industry are presented and their potential application for oil well cementing is discussed.

Current state of the art

In this section, recent studies carried out to improve the physical and mechanical characteristics of Portland cement are presented. It should be noted that many of these studies were done in the civil industry and there are a limited number of research works conducted to modify of oil well cements using nanomaterials. However, since a very same type of the cement is used in the civil and construction industry, the potential benefits and disadvantages of these nanomaterials in the primary/secondary cementing of wells can be understood.

Nanosilica (nanoSiO₂)

Nanosilica has been used in many studies for cement-based materials as it is the cheapest oxide nanoparticles (Ershadi et al. 2011; Choolaei et al. 2012). Qing et al. (2007) found that 3% wt nanosilica can reduce the amount of calcium hydrate (portlandite), and improves the compressive and bonding strength at the early stage of hardening. Ershadi et al. (2011) conducted an oil well cementing experiment by adding nanosilica into the class G cement. The water-to-cement ratio of 0.6 was used to produce a cement slurry with a large thickening time, high porosity, and permeability and a low compressive strength. They indicated that adding nanosilica improves the rheological and mechanical properties of the cement, while the porosity and permeability decreases by 33 and 99%, respectively. This could be due to the filler characteristics of nanosilica, which can enhance the microstructure and promote further pozzolanic reactions (Ershadi et al. 2011; Choolaei et al. 2012). The results obtained from the study of Choolaei et al. (2012) also emphasized on the great increase of the compressive strength after adding different portions of nanosilica into an ordinary Portland cement. They also indicated that the porosity and permeability of the cement decreases which was subjected to the quantity of nanosilica used. They concluded that a certain quantity of nanosilica must be added to the cement to achieve the desired functionality. A very similar conclusion was made by Mendes et al. (Mendes and Hotza, Repette 2014) as they highlighted that a large amount of nanosilica would reduce the performance of the cement, while a small amount would not make any significant changes. Choolaei et al. (2012) proposed to use 1 wt% and Oltulu and Şahin (2011) suggested 2 wt %, whereas Mendes et al. (Mendes and Hotza, Repette 2014) recommended 3 wt% nanosilica for being mixed with the cement to have the best performance. Nevertheless, these portions significantly increased the viscosity of the cement slurry by preventing the separation of cement particles.

However, the observation made by Ghafoori et al. (2016) was not aligned with the previous findings. They replaced their Portland cements (Class I) with 6 wt% nanosilica/microsilica and fully submerged the cement samples in a 5 wt% chemical sodium sulfate (Na₂SO₄) solution for 1 year. The results obtained indicated that the microsilica-based cement expands by 0.043%, whereas the nanosilica-based cement could swell by 0.054%. It was also observed that the compressive strength of 6 wt% nanosilica-based cement (~44 MPa) is lower than that of the microsilica-based cement (~52 MPa). Their mercury intrusion porosimetry (MIP) testing showed a higher volume of pores in the nanosilica mixture. These could be linked to the agglomeration effect of the dry nanosilica during mixing. They indicated that agglomerated nanosilica failed to be a nucleation site

for densifying the cement paste. Li et al. (2006) found that water could be trapped between the agglomerated structure of nanoparticles during mixing which later became a porous zone. This indicated the fact that agglomerated nanosilica had weakened the cement paste matrix. Hence, a proper dispersion would be needed to fully harness the nanoparticles in the cement slurry.

Nanoalumina (nanoAl₂O₃)

Several studies have been conducted to investigate the application of nanoalumina in the cement and concrete industry. Oltulu and Şahin (2011) studied the single and combined effects of nanopowders (i.e., nanoalumina and nanosilica) on the cement strength and capillary permeability. They added 0.5, 1.25, and 2.5 wt% binder amount of nanoparticles to the cement and tested the compressive strength at the early (i.e., 3 and 7 days), standard (i.e., 28 days), and late stages (i.e., 56 and 180 days), whereas the capillary permeability was only determined after 180 days. The best result for the compressive strength and the capillary permeability were observed when 1.25 wt% nanoalumina was used. They concluded that nanoalumina is a better option compared to nanosilica when it comes to the improvements of the physical and mechanical properties of the cement. They also indicated that a combination of these two nanoparticles would lead to agglomeration and reduces the overall performance of the cement mortar. Later, in a similar study, Oltulu and Şahin (2013) highlighted that 1.25 wt% single nanopowder would be good enough to maximize the compressive strength and minimize the permeability of the cement. Mendes et al. (Mendes and Hotza, Repette 2014) also pointed out that nanoalumina improves the abrasion resistance and thermal shock as well as resistance against any drastic changes in temperature. Heikal et al. (2015) partially replaced cement with 1, 2, 4, and 6 wt% nanoalumina to study their influences on the cement strength. Polycarboxylate-based superplasticizer was also used as part of this study to maintain the rheology of the cement slurry. The samples were cured for 28 days in a water bath and the results revealed that adding nanoalumina enhances the hydration of the cement by accelerating the initial and final setting times. The compressive strength was also increased for the slurry having superplasticizer. They concluded that 1 wt% nanoalumina is the optimum amount to achieve the desired properties.

To study the effect of sulfate attack on the cement, Jahan-gir and Kazemi (2014) added 0.1 kg nanosilica and 0.05 kg nanoalumina to the cement, cured the samples at the room temperature for 24 h, and exposed them to 10 wt% sulfuric acids for 3 to 28 days. Their study indicated that the compressive strength increases by 50% when nanoparticles are used. It was also found that a combination of nanoalumina

and nanosilica may result in a lesser expansion, since nanoalumina is a great gelatinous preserver.

Nanotitanium dioxide (nanoTiO₂)

Nanotitanium dioxide has been used in several studies with cement-based materials due to its functionalities, such as removal of volatile organic compounds and self-cleaning, which are commonly known as photocatalytic properties (Lee and Kurtis 2010; Chen et al. 2012). Unlike nanosilica, it is a non-reactive filler and has no pozzolanic activity (Chen et al. 2012). Zhang and Li (2011) conducted a test on the concrete and demonstrated that a small quantity of nanoTiO₂ may have a better performance than adding a large volume. According to them, adding 1 wt% nanotitanium dioxide would increase the compressive strength by 118%. This quantity could also reduce the porosity from 11 to 9%. They concluded that the finer the pore structure of the concrete is, the higher the resistance of the concrete would be against the chloride penetration. Senff et al. (2012) prepared cement samples with 12 wt% nanotitanium dioxide based on a water/binder weight ratio of 0.5 and did rheological and flow table measurements. They found that the torque, yield stress, and plastic viscosity of mortars increase significantly by this modification. However, changes in the mechanical properties, such as the compressive strength, were not obvious. According to the study carried out by Meng et al. (2012), where 0, 5, and 10 wt% nanoTiO₂ were mixed by the cement, the compressive strength decreases once 10 wt% nanotitanium dioxide were added to the cement. Similar results were shown by Perez-Nicolas et al. (Pérez-Nicolás et al. 2017) where they found that after 28 days of curing, increasing the amount of nanometrically structured TiO₂ in the cement decreased the compressive strength due to the increase of mixing water. Chen et al. (2012) used a similar percentage as Meng et al. (2014) and showed that the compressive strength increases at all ages. Besides, cement samples could withstand the corrosion and flame abrasion (Lee and Kurtis 2010). Mohseni et al. (2016) studied the application of nanoTiO₂ on rice hush ash-based cement composites. The percentage of nanoparticles used varies from 1 to 5 wt% of the binder, and the water-to-binder ratio of 0.4 was used to prepare the slurry. Improvements of the compressive strength and durability were recorded, especially for the mixture having 10 wt% rice hush ash and 5 wt% nanoTiO₂. They also observed reductions in the transfer properties with the increase of nanoadditives in the chloride permeability test.

Polymer/clay nanocomposites

Nanoclay is another nanomaterial which can be considered as a potential alternative for the modification of

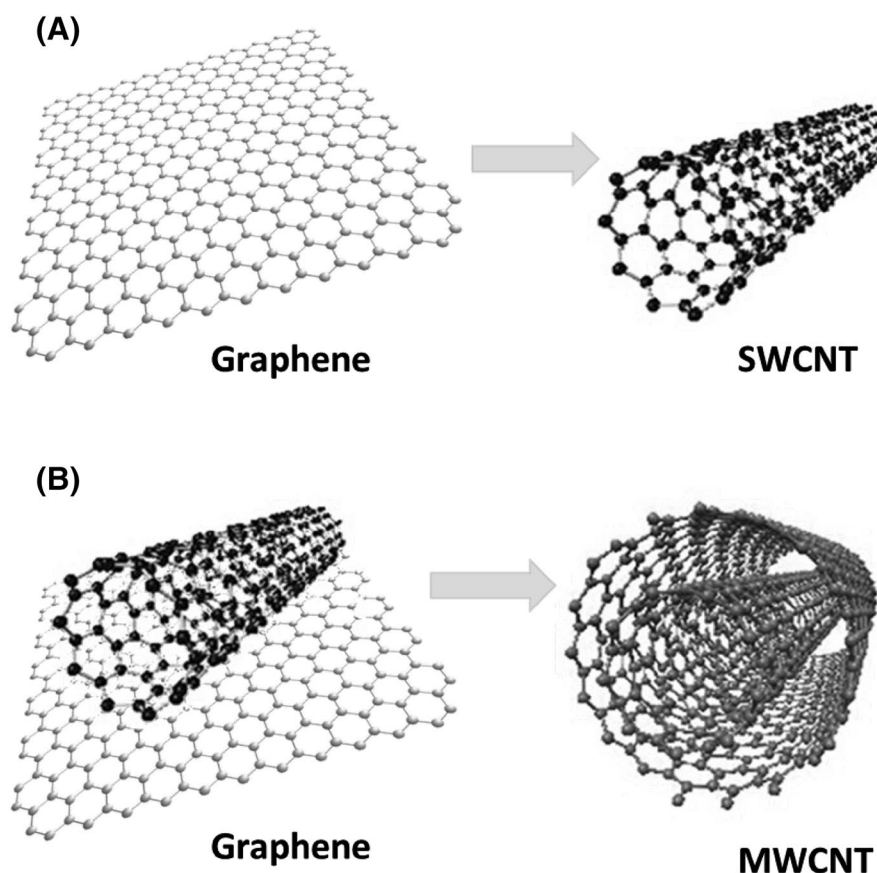
cement-based materials. Hakamy and Shaikh (Hakamy et al. 2014) carried out an experiment on hemp-fabric-reinforced nanocomposites by partially substituting ordinary Portland cement (OPC) with 1, 2, and 3 wt% nanoclay. The water-to-cement ratio was considered as 0.48, and it was found that 1 wt% nanoclay would be the optimum quantity required to improve the hemp-fabric, nanomatrix adhesion, and thermal stability. It would also reduce the porosity and water absorption, and increase the flexural strength, fracture toughness, and impact strength. The reduction of transport properties was highlighted by Surendra et al. (Surendra et al. 2015), as well. According to them, nanoclay has a two-layer structure which helps to block the water molecules transport and reduce the permeability of the cement mortar, which increases the compressive strength by 12% when 1 wt% kaolinite is added. The flexural strength of the cement paste was increased when 1 wt% kaolinite was added to the cement. Baueregger (2015) studied the use of nanoclay on the early cement strength. The kaolinite was used by different portion as the nanoclay. Their results showed that nanokaolin clay could boost the early compressive and tensile strength of the cement without negatively impacting the final strength after 28 days. They also pointed out that a proper dispersion technique and an optimum size selection would be critical factors to improve the overall performance of the cement. Hakamy et al. (2015) studied cement nanocomposites reinforced with hemp-fabric and calcined nanoclay (CNC) under the NaOH treatment. They reported that 1 wt% CNC reduces the porosity and water absorption and increases the flexural strength, fracture toughness, impact strength, and thermal stability. They also stated that a significant amount of CNC being used in the cement would cause agglomeration. As such, a proper dispersion method must be considered to ensure that clay nanoparticles can reinforce the cement structure.

Carbon nanotubes (CNTs)

Carbon nanotubes (CNTs) are hollow tubular channels, which are a rolled up version of the single or multiple layer graphene (Ferro et al. 2011). Their length is not restricted but often in micrometer size, while their diameters are something between 0.4 and 10 nm for a single-walled CNT (SWCNT) or from 4 to 100 nm for a multi-walled CNT (MWCNT). Figure 3 shows a schematic view of SWCNT and MWCNT.

CNTs were discovered by Iijima (1991) as the materials exhibit outstanding mechanical, thermal, and conductive properties. This ultralight weight material has been involved in different studied ranging from medicinal and constructions to buildings of structures ever since. There have also been a few studies on the application of CNTs in the oil well cementing where improvements in the compressive strength (Nasibulina et al. 2010), ductility (Abu Al-Rub et al. 2012),

Fig. 3 a SWCNT and b MWCNT structures (<http://www.nanocarbon.cz>)



resilience (Yazdanbakhsh et al. 2009), and Young's modulus (Sáez de Ibarra et al. 2006) were reported.

For instance, Tyson (Tyson et al. 2011) indicated that CNT can increase the fracture toughness and prevent the creation of crack induced due to the expansion. It was also found that the rheology and stability of the cement slurry will not be altered if a sophisticated dispersion technique is employed (de Paula et al. 2014). Moreover, CNTs can increase the stiffness of C–S–H and decrease the porosity of the cement matrix, which ultimately reinforce the cement (Ferro et al. 2011). Rahimirad and Baghbadorani (2012) studied the use of CNT-reinforced cements in preventing gas migration, which is one of the cementing problems in gas wells. They concluded that the probability of having casing failure in oil and gas wells can be reduced, because CNTs have a high aspect ratio and, hence, would require significant energies to allow the crack propagation around a tube. However, to have an efficient CNT synthesized cement, a proper dispersion technique must be used and an optimum quantity of CNTs must be found. de Paula et al. (2014) dispersed the single-layered carbon nanotube (SWCNT) into the ground cement clinker using lignosulfonate. Although the results were promising, the scanning electron microscopic images did not show the perfect bonds between the cement matrix and SWCNT, which indicate the inefficiency

of the dispersion technique applied. Mendoza et al. (Mendoza Reales et al. 2016) indicated that addition of MWCNTs by the mass of cement up to 0.5% in an anionic surfactant can help to have a good dispersion. There was no negative impact or chemical affinity reported to the cement in that study, even at the temperature of 65 °C.

On the contrary, the study of Camacho et al. (2014) concluded that the incorporation of MWCNTs in the cement would lead to a higher corrosion rate. In their study, they considered a water-to-cement ratio of 0.5 with 0.05, 0.1, 0.25, and 0.5 wt% MWCNTs dosage to the cement. Distilled water was used for the sample preparation and the cement pastes were fabricated in 20 °C and 65% relative humidity (RH) for 28 days. Prismatic specimens were prepared for two corrosion tests: (1) chloride attack tests conducted by partially immersion of the specimens in a brine solution and (2) accelerated carbonation tests where samples were exposed to dry and wet CO₂. The results obtained from both tests were similar and revealed that the increasing MWCNT dosage increases the corrosion rate. These could be explained with the depassivation of the steel surface which was due to a pH decrease induced by the cement carbonation. However, this corrosion study was based on the electrode interactions which could not be considered as an approach to directly observe the behavior of MWCNT-based cements.

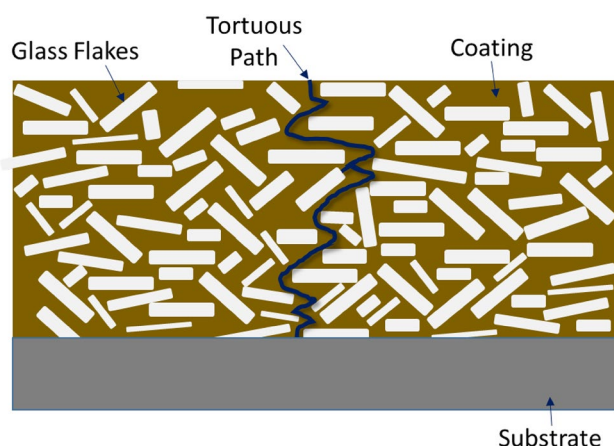


Fig. 4 Appearance of GFs in a coated substrate

Nanoglass flake (NGFs)

Glass flake (GF) substrates are defined as highly planar platelets with a very smooth surface. They are transparent with a transparent color tone. Nanoglass flakes (NGFs) were introduced early in 2010, having a thickness of 100–750 nm. Because of the layered structure, GFs have many advantages over other nanomaterials, such as providing a better interaction between filler and matrix, which improves the overall properties of the final cement product (see Fig. 4) (Nematollahi et al. 2010; Salehi et al. 2017).

As it is seen in Fig. 4, the laminar structure of NGFs creates a tortuous path, preventing any particles to intrude into the substrate easily. Since their introduction in the coating industry in the 1960s, GFs have been widely used in a variety of different applications due to their excellent material improvements. GFs can also improve the chemical and corrosion resistance properties of materials (Nematollahi et al. 2010; Ghadami et al. 2014). Moreover, they have been extensively used as an in-situ barrier for many industrial applications, such as external coating of high-temperature oil flow lines in Duri Oil Field, Indonesia (Watkinson 2009). Watkinson (2009) in his study on the concrete indicated that NGFs are capable of enhancing the chemical resistance and the compressive and tensile strength of materials. Considering the fact that NGFs can provide a tough impermeable barrier for steel and concrete surfaces by generating the tortuous paths, they might be a good option to improve the cement properties under the severe and abrasive conditions of CO₂ storage sites. According to Salehi et al. (2017), by adding 0.5 wt% GFs, a lesser amount of fillers would be required for the cement preparation, which reduces the manufacturing costs and fabricating substances in many industrial applications. However, there have not been any studies so far reporting the application of NGFs in the oil well cementing and, hence,

their behaviors under the HPHT condition of CO₂ sequestration conditions have not been fully understood.

Conclusion

There have been many studies proposing solutions to improve the overall performance of the cements used in CO₂ sequestration sites, but none of these approaches were totally successful in resolving these issues, due, perhaps, to the severity of interactions between the cement and supercritical CO₂. Nanoparticles have revealed promising results once added to the cement in various conditions, which might be due to their large surface area and reactivity. It seems that almost all types of nanomaterials can act like a filler to densify the microstructure, reduce the porosity, improve the transfer properties, and, eventually, enhance the mechanical strength. However, it appears that combination of two or more nanoparticles can lead to agglomeration and creates unfavorable changes in the cement properties. Superplasticizer, as a dispersant agent, may help to have a better and uniform dispersion of nanoparticles in the cement structure, but there is no established approach to determine the amount of nanoparticles required to have an efficient cement under different conditions.

Nanosilica might be one of the best nanoparticles for the cement probably due to its lower cost and pozzolanic activity. Nanoclay is also cheap, but it is not as much good as nanosilica due to its lesser pozzolanic activity. NanoAl₂O₃ has a better performance compared to nanoSiO₂, but it is not commonly used, perhaps, because of cost-saving purposes. NanoTiO₂ has no pozzolanic activity, but it has photocatalytic properties, which can help to decrease the migration of CO₂. However, Nanotitanium dioxide may not be suitable for CO₂ sequestrated sites due to its instability under high-temperature and high-pressure conditions. CNTs and NGFs can withstand harsh environments, but there are a limited number of studies reporting their applications in the oil well cementing. Thus, further studies are recommended to evaluate the application of these nanoparticles when they are mixed in the cement and exposed to CO₂.

Acknowledgements The authors would like to acknowledge the Ministry of Higher Education (MoHE) in Malaysia to fund this research through the Fundamental Research Grant Scheme (FRGS) under the grant number FRGS/1/2015/TK05/CURTIN/03/4.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Abid K, Gholami R, Choate P, Nagaratnam BH (2015) A review on cement degradation under CO₂-rich environment of sequestration projects. *J Nat Gas Sci Eng*. <https://doi.org/10.1016/j.jngse.2015.09.061>
- Abu Al-Rub RK, Ashour AI, Tyson BM (2012) On the aspect ratio effect of multi-walled carbon nanotube reinforcements on the mechanical properties of cementitious nanocomposites. *Constr Build Mater* 35:647–655
- Adams N, Charrier T (1985) Drilling engineering: a complete well planning approach. PenWell Publishing Company, Tulsa
- Ansarizadeh M, Dodds K, Gurpinar D, Kalfa U, Ramakrishnan TS, Sacuta N, Whittaker S (2015) Carbon dioxide—challenges and opportunities. *Oilfield Rev* 27(2)
- Arina S, Irawan S (2010) Effects of pressure and temperature on well cement degradation by supercritical CO₂. *International Journal of Engineering and Technology IJET-IJENS*
- Bachu S, Bennion DB (2009) Experimental assessment of brine and/or CO₂ leakage through well cements at reservoir conditions. *Int J Greenhouse Gas Control* 3(4):494–501
- Bai M, Sun J, Song K, Li L, Qiao Z (2015) Well completion and integrity evaluation for CO₂ injection wells. *Renew Sustain Energy Rev* 556–564
- Barlet-Gouedard V, Rimmelé G, Porcherie O, Quisel N, Desroches J (2009) A solution against well cement degradation under CO₂ geological storage environment. *Int J Greenhouse Gas Control* 3(2):206–216
- Barlet-Gouedard V, James S, Drochon B, Piot B, Jean-Philippe C (2012) Cement composition for carbon dioxide supercritical environment. US Patent (US) 8,091,642 B2
- Barlet-Gouedard V, Rimmelé G, Goffé B, Porcherie O (2007) Well technologies for CO₂ geological storage: CO₂-resistant cement. *Oil Gas Sci Technol Rev IFP* 62(3):1–12
- Baueregger S, Lei L, Perello M, Plank J (2015) Use of a nano clay for early strength enhancement of portland cement. *Nanotechnology in Construction*
- Benge G (2009) Improving wellbore seal integrity in CO₂ injection wells. *Soc Petrol Eng*. <https://doi.org/10.2118/119267-MS>
- Benson SM, Cole DR (2008) CO₂ sequestration in deep sedimentary formations. *Element* 4:325–331
- Brandl A, Cutler J, Seholm A, Sansil M, Braun G (2010) Cementing solutions for corrosive well environments
- Camacho MDC, Galao O, Baeza FJ, Zornoza E, Garcés P (2014) Mechanical properties and durability of CNT cement composites. *Materials* 7:1640–1651
- Chang TP, Shih JY, Yang KM, Hsiao TC (2007) Material properties of portland cement paste with nano-montmorillonite. *J Mater Sci* 42(17):7478–7487
- Chen J, Kou SC, Poon CS (2012) Hydration and properties of nano-TiO₂ blended cement composites. *Cement Concrete Compos* 34(5):642–649
- Choolaei M, Rashidib AM, Ardjmandi M, Yadegarib A, Soltanianb H (2012) The effect of nanosilica on the physical properties of oil well cement. *Mater Sci Eng A* 538:288–294
- de Paula JN, Calixto JM, Ladeira LO, Ludvig P, C.Souza TC, Rocha JM, de Melo AAV (2014) Mechanical and rheological behavior of oil-well cement slurries produced with clinker containing carbon nanotubes. *J Petrol Sci Eng* 122:274–279
- Duguid A, Scherer GW (2010) Degradation of oil well cement due to exposure to carbonated brine. *Int J Greenhouse Gas Control* 4(3):546–560
- Ershadi V, Ebadi T, Rabani AR, Ershadi L, Soltanian H (2011). The effect of nanosilica on cement matrix permeability in oil well to decrease the pollution of receptive environment. *Int J Environ Sci Dev* 2(2)
- Ferro G, Tulliani JM, Musso S (2011) Carbon nanotubes cement composites. *Cassino (FR)* 13–15
- Gaurina-Medimurec N, Pašić B, Simon K (2010) CO₂ underground storage and wellbore integrity. *The International Journal of Transport and Logistic*
- Ghadami A, Ehsani M, Khonakdar HA (2014) Vinyl ester/glass flake nanocomposites: an overview of chemical and physical properties. *J Compos Mater* 48(13):1585–1593
- Ghafoori N, Batilov IB, Najimi M (2016) Sulfate resistance of nanosilica and microsilica contained mortars”. *ACI Mater J* 113(4):459–469
- Hakamy A, Shaikh FUA, Low IM (2014) Thermal and mechanical properties of hemp fabric reinforced nanoclay-cement nanocomposites. *J Mater Sci* 49(4):1684–1694
- Hakamy A, Shaikh FUA, Low IM (2015) Thermal and mechanical properties of NaOH treated hemp fabric and calcined nanoclay-reinforced cement nanocomposites. *Mater Des* 80:70–81
- Heikal M, Ismail MN, Ibrahim NS (2015) Physico-mechanical, microstructure characteristics and fire resistance of cement pastes containing Al₂O₃ nano-particles. *Constr Build Mater* 91:232–242
- Hui C, Li ZZ, Yue DX (2004) Metapopulation dynamics and distribution, and environmental heterogeneity induced by niche construction. *Ecol Model* (177):107–118
- Iijima S (1991) Helical microtubules of graphitic carbon. *Nature* 354:56–58
- International Energy Agency (2015) Carbon capture and storage: The solution for deep emissions reductions. IEA
- IPCC (2005) Underground geological storage. IPCC Special Report on Carbon Dioxide Capture and Storage
- Jahangir S, Kazemi S (2014) Effect of nano-alumina (N-Al) and nanosilica (NS) as admixtures on concrete behavior. *International Conference on Advances in Agricultural, Biological and Environmental Sciences*
- Kutchko B, Strazisar B, Dzombak D, Lowry G, Thaulow N (2007) Degradation of well cement by CO₂ under geologic sequestration conditions. *Environ Sci Technol* 41:4787–4792
- Kutchko B, Strazisar B, Dzombak D, Lowry G, Thaulow N (2008) Rate of CO₂ attack on hydrated class H well cement under geologic sequestration conditions. *Environ Sci Technol* 42(16):6237–6242
- Laudet JB, Garnier A, Neuville N, Le Guen Y, Fourmaintraux D, Rafai N, Shao JF (2011) The behavior of oil well cement at downhole CO₂ storage conditions: Static and dynamic laboratory experiments. *Energy Procedia* 4:5251–5258
- Lee BY (2012) Effect of titanium dioxide nanoparticles on early age and long term properties of cementitious materials. Georgia Institute of Technology Publication
- Lee BY, Kurtis KE (2010) Influence of TiO₂ nanoparticles on early C3S hydration. *J Am Ceram Soc* 93(10):3399–3405
- Lesti M, Tiemeyer C, Plank J (2013) CO₂ stability of Portland cement based well cementing systems for use on carbon capture and storage (CCS) wells. *Cem Concr Res* 45:45–54
- Li ZH, Wang HF, He S, Lu Y, Wang M (2006) Investigations on the preparation and mechanical properties of the nano-alumina reinforced cement composite. *Mater Lett* 60:356–359
- MacLaren DC, White MA (2003) Cement: its chemistry and properties. *J Chem Educ* 8(6):623
- Mendes TM, Hotza, Repette WL (2014) Nanoparticles in cement based material: a review. *Adv Mater Sci* 40(1):89–96
- Mendoza Reales OA, Pearl WC Jr, Paiva MDM, Miranda CR, Toledo Filho RD (2016) Effect of a commercial dispersion of multi walled carbon nanotubes on the hydration of an oil well cementing paste. *Front Struct Civ Eng* 10(2):174–179

- Meng T, Yu Y, Qian X, Zhan S, Qian K (2012) Effect of nano-TiO₂ on the mechanical properties of cement mortar. *Constr Build Mater* 29:241–245
- Mohseni E, Naseri F, Amjadi R, Khotbehsara MM, Ranjbar MM (2016) Microstructure and durability properties of cement mortars containing nano-TiO₂ and rice husk ash. *Constr Build Mater* 114:656–664
- Nasibulina NI, Anoshkin IV, Shandakov SD, Nasibulin AG, Cwirzen A, Mudimela PR, Cwirzen KH, Malm JEM, Koltsova TS, Tian Y, Vasilieva ES, Penttala V, Tolochko OV, Karppinen MJ, Kauppinen EI (2010) Direct synthesis of carbon nanofibers on cement particles. *Transp Res Rec J Transp Res Board* 214:96–101
- Nelson EB (1990) Well cementing. Sugar Land, TX, Schlumberger Educational Services, Texas
- Nematollahi M, Heidarian M, Peikari M (2010) Comparison between the effect of nanoglass flake and montmorillonite organo-clay on corrosion performance of epoxy coating. *Corros Sci* 52:1809–1817
- Oldenburg C (2007) Migration mechanisms and potential impacts of CO₂ leakage and seepage. In: Wilson EJ, Gerard D (eds) Carbon capture and sequestration: Integrating Technology, Monitoring, Regulation
- Oltulu M, Şahin R (2011) Single and combined effects of nano-SiO₂, nano-Al₂O₃ and nano-Fe₂O₃ powders on compressive strength and capillary permeability of cement mortar containing silica fume. *Mater Sci Eng* 528(22–23):7012–7019
- Oltulu M, Şahin R (2013) Effect of nano-SiO₂, nano-Al₂O₃ and nano-Fe₂O₃ powders on compressive strengths and capillary water absorption of cement mortar containing fly ash: a comparative study. *Energy Build* 58:292–301
- Omosibi O, Maheshwari H, Ahmed R, Shah S, Osisanya S, Hassani S, DeBruijn G, Cornell W, Simon D (2016) Degradation of well cement in HPHT acidic environment: effects of CO₂ concentration and pressure. *Cement Concrete Compos* 74:54–70
- Pérez-Nicolás M, Navarro-Blasco I, Fernández JM, Alvarez JI (2017) The effect of TiO₂ doped photocatalytic nano-additives on the hydration and microstructure of portland and high alumina cements. *Nanomaterials* 7(10):329
- Qing Y, Zenan Z, Deyu K, Rongshen C (2007) Influence of nano-SiO₂ addition on the properties of hardened cement paste compared with silica fume. *Constr Build Mater* 21:537–542
- Rahimirad M, Baghbadorani JD (2012) Properties of oil well cement reinforced by carbon nanotubes. *SPE*
- Sáez de Ibarra Y, Gaitero JJ, Erkizia E, Campillo I (2006) Atomic force microscopy and nanoindentation of cement pastes with nanotube dispersions. *Phys Status Solidi (A)*
- Salehi S, Ehsani M, Khonakdar HA (2017) Assessment of thermal, morphological, and mechanical properties of poly(methyl methacrylate)/glass flake composites. *J Vinyl Addit Technol*
- Sanchez F, Sobolev K (2010) Nanotechnology in concrete—a review. *Constr Build Mater* 24(11):2060–2071
- Santra A, Sweatman R (2011) Understanding the long-term chemical and mechanical integrity of cement in a CCS environment. *Energy Proc* 4:5243–5250
- Senff L, Hotza D, Lucas S, Ferreira VM, Labrincha JA (2012) Effect of nano-SiO₂ and nano-TiO₂ addition on the rheological behavior and the hardened properties of cement mortars. *Mater Sci Eng A* 532:354–361
- Sobolev K (2015) Nanotechnology and nanoengineering of construction materials. *Nanotechnol Constr* 3–15
- Surendra PS, Hou P, Cheng X (2015) Durability of cement-based materials and nano-particles: a review. *Nanotechnol Const*
- Takase K, Barhate Y, Hashimoto H, Lunkad SF (2010) Cement-sheath wellbore integrity for CO₂ injection and storage wells. *SPE*
- Tyson BM, Abu Al-Rub RK, Yazdanbakhsh A, Grasley Z (2011) Carbon nanotubes and carbon nanofibers for enhancing the mechanical properties of nanocomposite cementitious materials. *J Mater Civ Eng* 23(7)
- Waseem Arshad M, Fosbøl PL, von Solms N, Thomsen K (2017) CO₂ capture with liquid-liquid phase change solvents: a thermodynamic study. *Energy Procedia*
- Watkinson CJ (2009) Heavy duty glass flake coatings for arduous anti-corrosion service. *Nace International Corrosion Conference and Expo*
- Xu T, Apps JA, Pruess K, Yamamoto H (2007) Numerical modeling of injection and mineral trapping of CO₂ with H₂S and SO₂ in a sandstone formation. *Chem Geol* 242(3–4):319–346
- Yazdanbakhsh A, Grasley Z, Tyson B, Abu Al-Rub R (2009) Carbon nanofibers and nanotubes in cementitious materials: Some issues on dispersion and interfacial bond. *ACI Spec Publ* 267:21–34
- Zhang MH, Li H (2011) Pore structure and chloride permeability of concrete containing nano-particles for pavement. *Constr Build Mater* 25(2):608–616
- Zhang M, Talman S (2014) Experimental study of well cement carbonation under geological storage conditions. *Energy Proc* 63:5813–5821
- Zhang LW, Dzombak DA, Nakles DV, Hawthorne SB, Miller DJ, Kutcho BG, Lopano CL, Strazisar BR (2013) Characterization of pozzolan-amended wellbore cement exposed to CO₂ and H₂S gas mixtures under geologic carbon storage conditions. *Int J Greenhouse Gas Control* 19:358–368
- Zhang LW, Dzombak DA, Nakles DV, Hawthorne SB, Miller DJ, Kutcho B, Lopano C, Strazisara B (2014) Effect of exposure environment on the interactions between acid gas (H₂S and CO₂) and pozzolan-amended wellbore cement under acid gas co-sequestration conditions. *Int J Greenhouse Gas Control* 27:309–318

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.